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Paleoceanography

Supporting Information for

Quantifying the stability of the planktic foraminifera physical niche between the Holocene and Last Glacial Maximum

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Contents of this file

Additional Supporting Information (Files uploaded separately)

Dataset S1. Relative abundance data for planktic foraminifera species for the modern and Last Glacial Maximum (data taken from the MARGO project (Kucera et al., 2005a; Barrows & Juggins, 2005, Chen et al., 2005). Raw abundances were converted to relative abundances. Abundance thresholds for the focal species 'optimum' niche were selected where there were strong increases in relative abundance and compared to an independent assessment of the optimal niche based on maximum test body sizes determined by Schmidt *et al*. (2004; 2006). These were defined as followed: *N. pachyderma* (40%), *G. bulloides* (30%), *T. truncatulinoides* (8%), *T. sacculifer* (15%), *G. ruber* (white) (35%) and *G. ruber* (pink) (6%).

Introduction

The following supporting information include figures and tables which support the main article and also include preliminary niche analyses. Figures S1 – S9 and Tables S1- S5 show results for ENM and ordination analyses for the realized niche (i.e. raw abundance data used). Figures S10 – S14 and Tables S6 – S10 show results for ENM and ordination analyses for the optimal niche (relative abundance data used to set thresholds to define niche optima).

Figure S1(a – f) show MaxEnt jackknife estimates of variable importance to global modern ENM fit. Each environmental variable is excluded in turn and a model created with the remaining variables. A model is then created using each variable in isolation. This identifies the variables that contribute the most to model test gain, as well as those that contain the most information not present in the other variables (Phillips et al. 2006).

Text S1.

Testing the impact of preservation (Figure S3a-b) : To test ENM sensitivity to selective dissolution of species within core-top samples, we compared outputs from the full occurrence dataset spanning the entire range of water depths (~ 50 - 5500 m) against a subset of the data containing only sites above 3000 m water depth in the North Atlantic for *Globigerinoides ruber* (pink; high dissolution susceptibility) and *Neogloboquadrina pachyderma* (low dissolution susceptibility) (Hemleben et al., 1989*)*. The calcite lysocline occurs between 4 - 5 km deep in the Atlantic (Zeebe & Wolf-Gladrow, 2001); thus at sites >3000 m water depth we expect carbonate microfossils to have experienced some dissolution. However, it is important to note that the MARGO data has been selected to avoid major dissolution biases and hence we likely will underestimate the potential impact of dissolution. Total species occurrences for the North Atlantic were: *N. pachyderma* (324) and *G. ruber* (pink) (354). For the < 3000m depth subset: *N. pachyderma* (238) and *G. ruber* (pink) (105). ENMs calibrated with the North Atlantic depth subset (< 3000 m) showed little difference in predictive performance compared to ENMs that included the full range of water sample depths for *G. ruber* (pink) and *N. pachyderma* (Figure 4). They also indicate a similar magnitude of change in model performance for each species dataset despite very different dissolution susceptibilities (*G. ruber* (pink), AUC = 0.82 for the full and depth subset data; *N. pachyderma*, AUC = 0.89 for the full dataset vs. 0.91 for the depth subset data). In both cases the models continue to produce good predictions that are consistent with species occurrences.

Text S2.

ENM predictive performance: binomial test. To assess the predictive performance of ENM projections to the LGM we used a binomial test; this determines if a model prediction is better than random by assessing the agreement between ENM projections of environmental suitability with independent LGM foraminifera occurrence data. This requires the use of thresholds to define binary environmentally suitable or unsuitable areas to assess model performance. We applied three thresholds here: 0%, or the "least training presence threshold" (sensu, Pearson et al., 2007), 90% fossil occurrences included and 50% fossil occurrences included) The least training presence threshold uses the lowest suitability value associated with an occurrence record and assumes that taxa are restricted to locations at least as suitable as those at which the species are observed at, and that sites at or above that threshold are suitable for the species. This defines a minimum area within which the organism can occur, but ensures that no presence records are incorrectly predicted. However, this approach can result in overly restricted model predictions, i.e. in cases of few occurrences for evaluation, or alternatively overly broad model predictions if occurrences are from sink populations, incorrectly geo-referenced or sensitive to variables that are not included in the environmental data (Peterson et al., 2011). Due to this possibility I applied multiple thresholds to assess the sensitivity of results to this value.

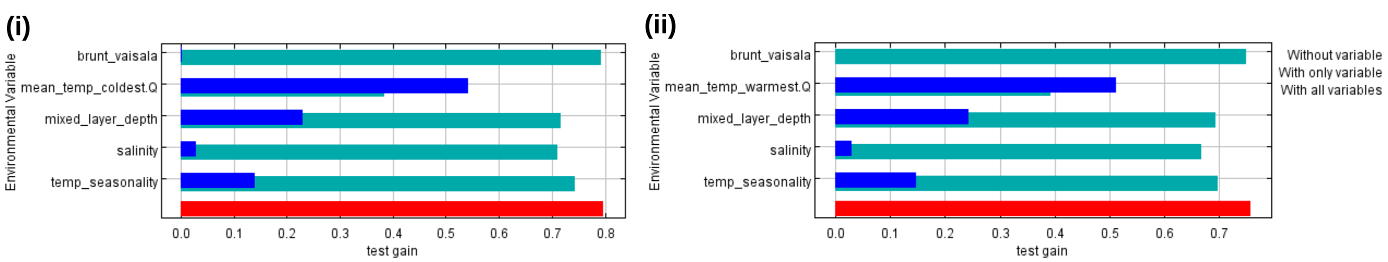

Figure S1a MaxEnt jackknife tests of average variable importance to model test gain for *N. pachyderma* global modern ENMs: model calibration with mean temperature of the coldest (i) and (ii) warmest quarters.

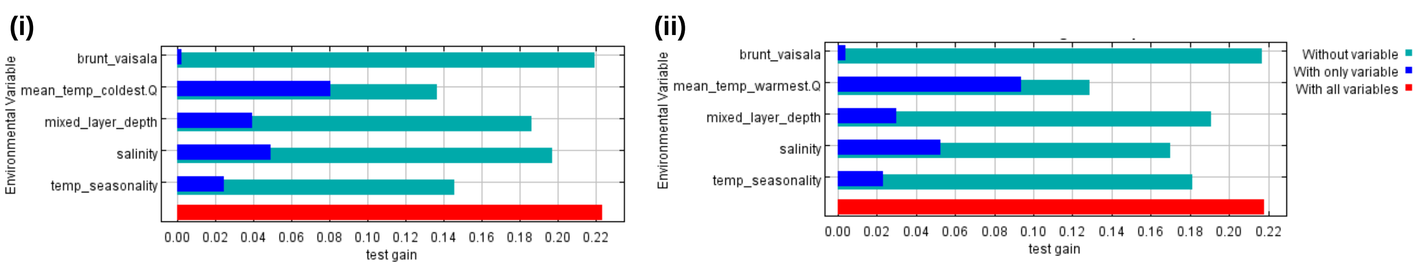

Figure S1b Maxent jackknife tests of average variable importance to model test gain for *G. bulloides* global modern ENMs: model calibration with mean temperature of the coldest (i) and (ii) warmest quarters.

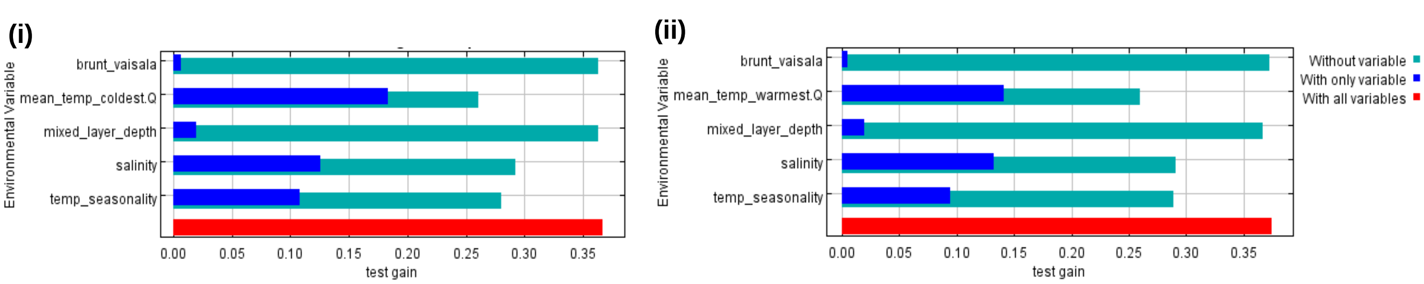

Figure S1c Maxent jackknife tests of average variable importance to model test gain for *T. truncatulinoides* global modern ENMs: model calibration with mean temperature of the coldest (i) and (ii) warmest quarters.

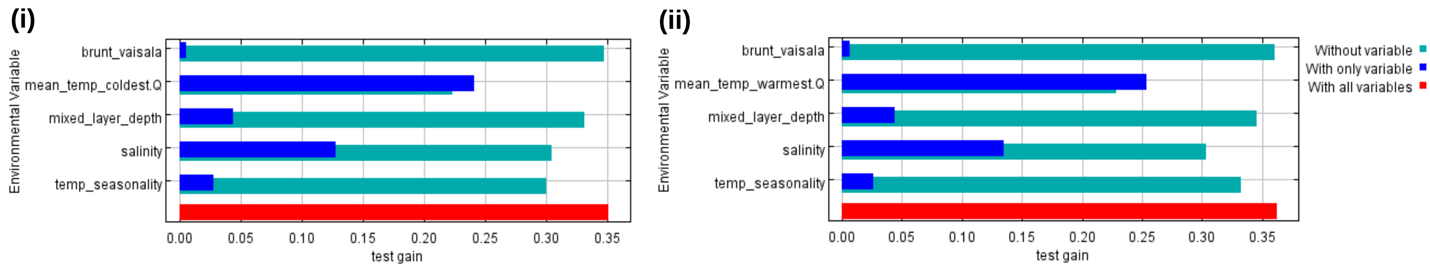

Figure S1d Maxent jackknife tests of average variable importance to model test gain for *G. ruber* (white) global modern ENMs: model calibration with mean temperature of the coldest (i) and (ii) warmest quarters.

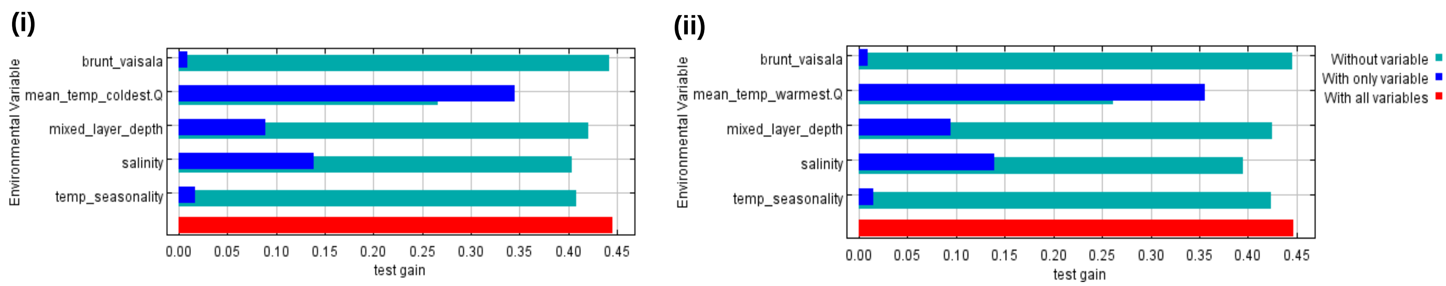

Figure Ss1e Maxent jackknife tests of average variable importance to model test gain for *T. sacculifer* global modern ENMs: model calibration with mean temperature of the coldest (i) and (ii) warmest quarters.

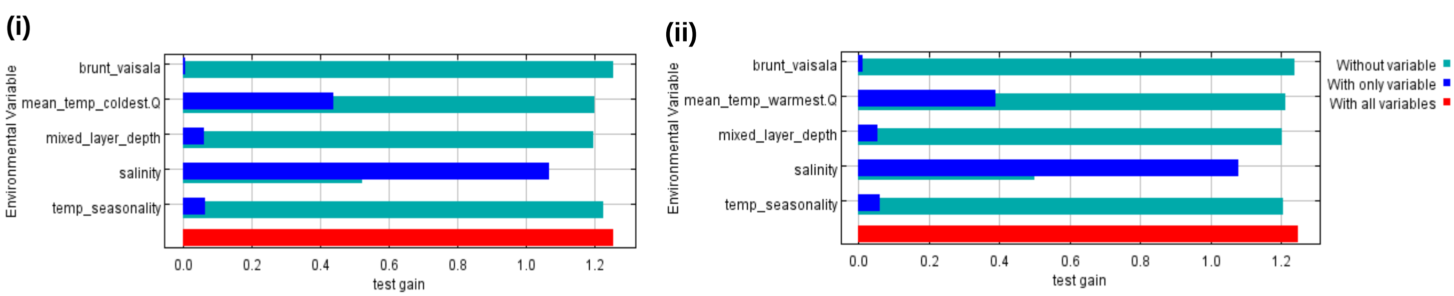

Figure S1f Maxent jackknife tests of average variable importance to model test gain for *G. ruber* (pink) global modern ENMs: model calibration with mean temperature of the coldest (i) and (ii) warmest quarters.

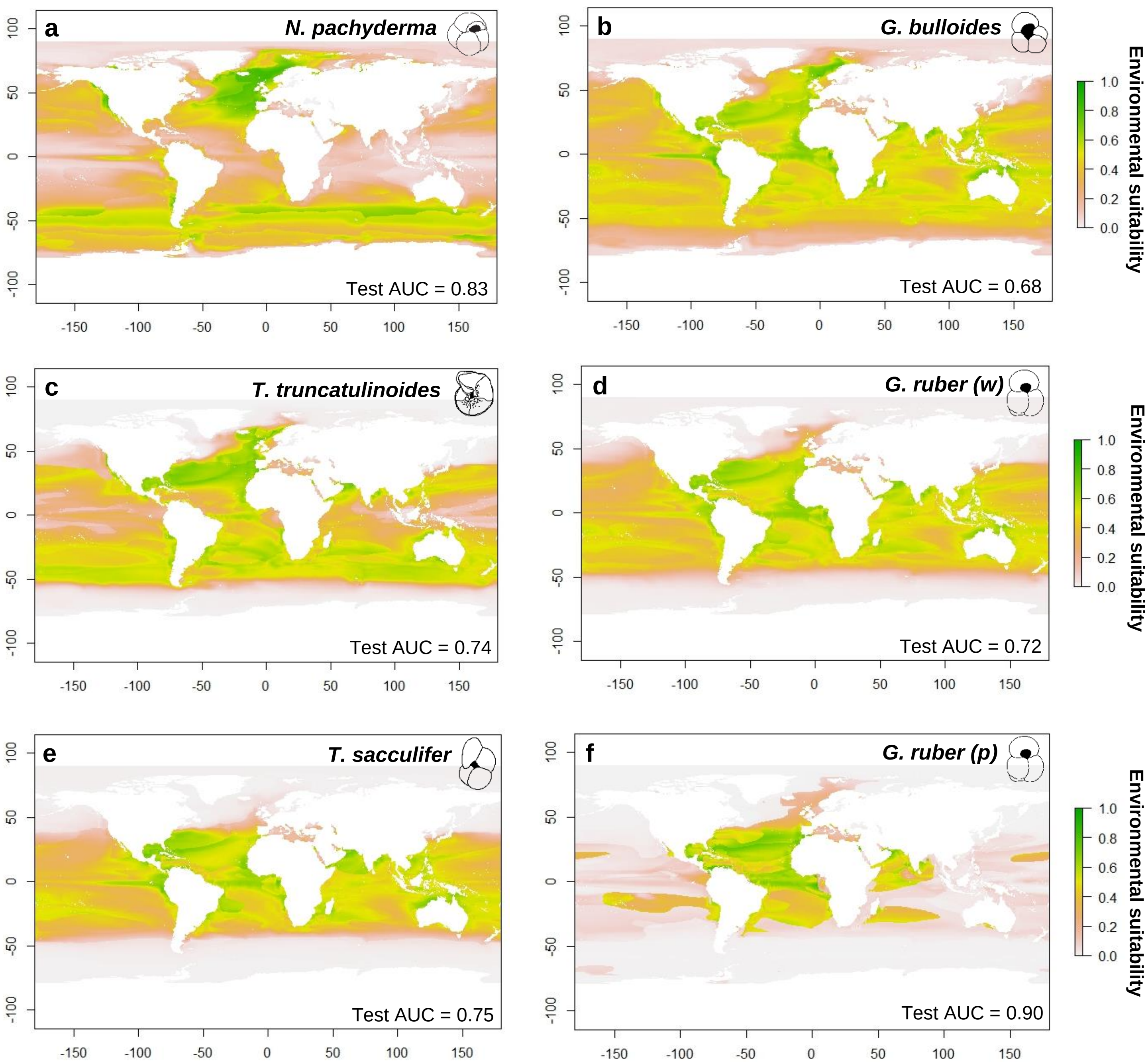

Figure S2a. MaxEnt ENMs calibrated in the modern ocean using all available data and projected globally: (a) *Neogloboquadrina pachyderma*, (b) *Globigerina bulloides*, (c) *Truncorotalia truncatulinoides*, *(d) Globigerinoides ruber* (white), (e) *Trilobatus sacculifer*, and (f) *G. ruber* (pink). Models calibrated with mean temperature of the coldest quarter. Dark green colour (and higher values) indicates high environmental suitability for species, light-green/yellow indicates intermediate suitability and pink/white (lower values) indicates poor suitability for species. Average test AUC scores (AUC) are a measure of predictive performance and show the fit of MaxEnt models to test occurrence data not included in model calibration.

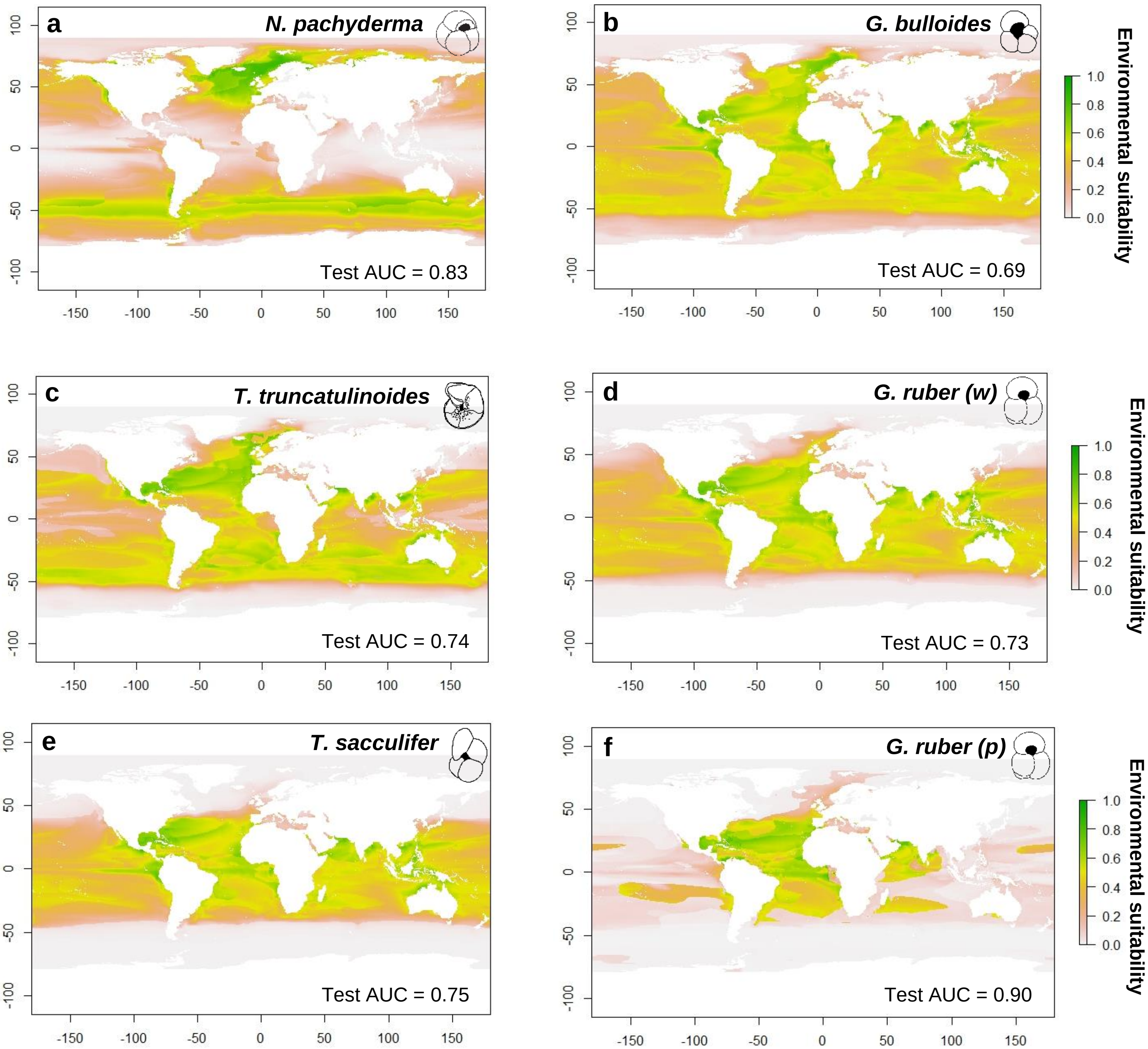

Figure S2b. MaxEnt ENMs calibrated in the modern ocean using all available data and projected globally: (a) *Neogloboquadrina pachyderma*, (b) *Globigerina bulloides*, (c) *Truncorotalia truncatulinoides*, *(d) Globigerinoides ruber* (white), (e) *Trilobatus sacculifer*, and (f) *G. ruber* (pink). Models calibrated with mean temperature of the warmest quarter. Dark green colour (and higher values) indicates high environmental suitability for species, light-green/yellow indicates intermediate suitability and pink/white (lower values) indicates poor suitability for species. Average test AUC scores (AUC) are a measure of predictive performance and show the fit of MaxEnt models to test occurrence data not included in model calibration.

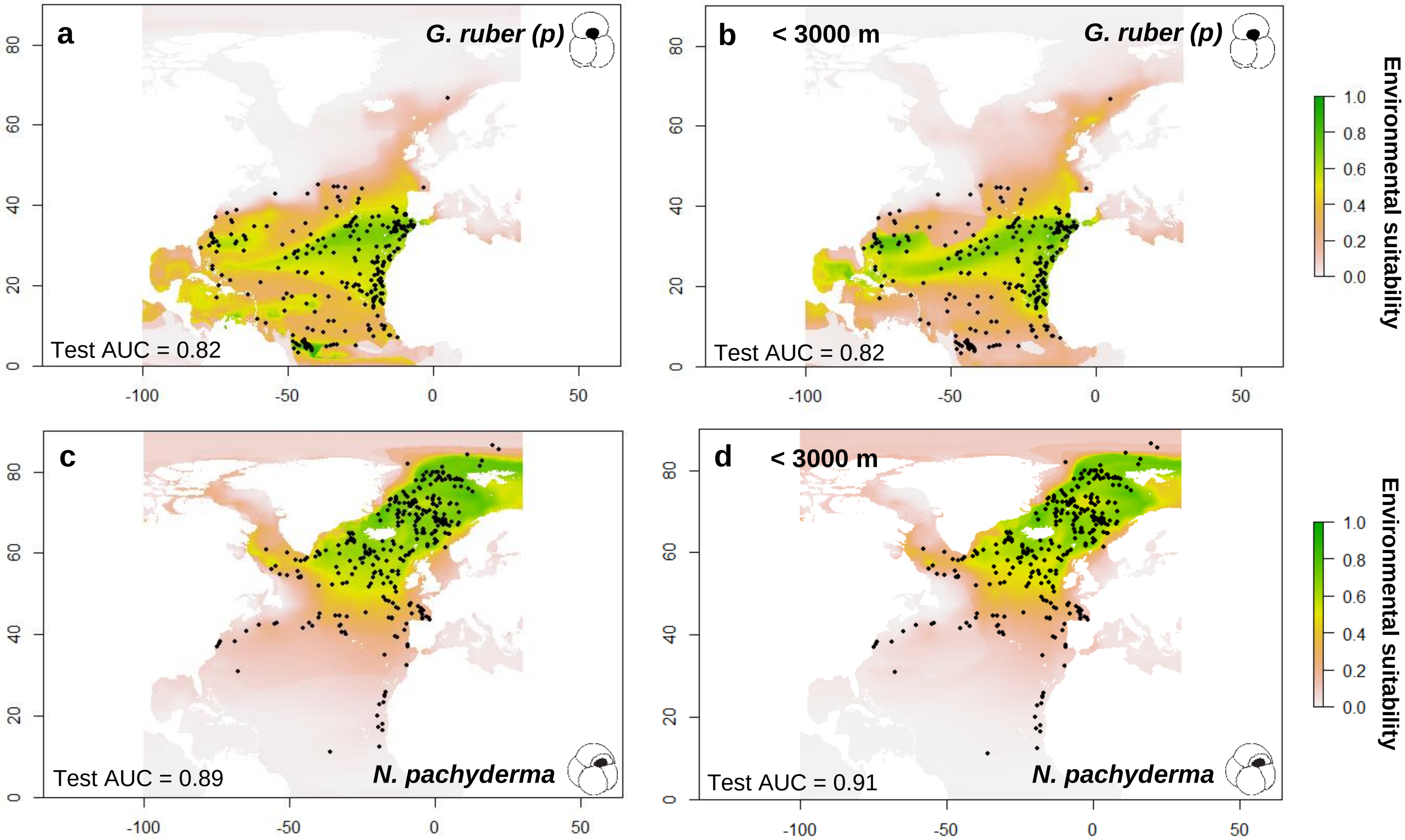

Figure S3a. Sensitivity of ENMs to changes in planktic foraminiferal assemblage composition caused by dissolution. MaxEnt model predictions for the modern North Atlantic are calibrated using the full occurrence dataset (water depths ~ 50 - 5000 m) for dissolution susceptible *Globigerinoides ruber* (pink) in ***a*** and dissolution resistant *Neogloboquadrina pachyderma* in ***c***. Models are calibrated using the temperature of the coldest quarter. Predictions based on a calibration for sites at <3000 m water depth only for (b) *G. ruber* (pink) and (d) *N. pachyderma*. Species occurrences (●) are overlaid on environmental suitability maps. Average test AUC scores (AUC) are measures of predictive performance and show the fit of MaxEnt models to test occurrence data not included in model calibration.

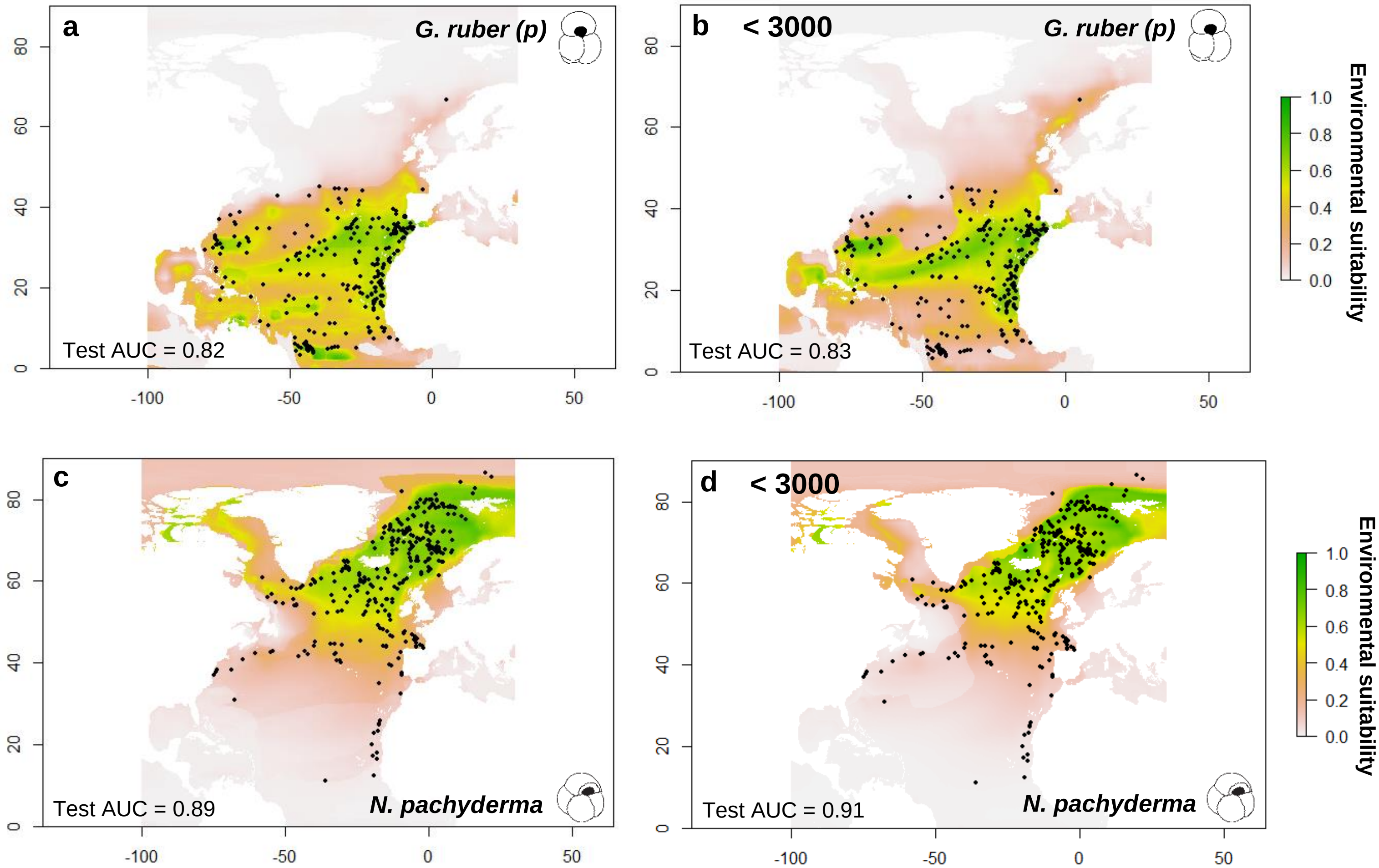

Figure S3b. Sensitivity of ENMs to changes in planktic foraminiferal assemblage composition caused by dissolution. MaxEnt model predictions for the modern North Atlantic are calibrated using the full occurrence dataset (water depths ~ 50 - 5000 m) for dissolution susceptible *Globigerinoides ruber* (pink) in ***a*** and dissolution resistant *Neogloboquadrina pachyderma* in ***c***. Models are calibrated using the temperature of the warmest quarter. Predictions based on a calibration for sites at <3000 m water depth only for (b) *G. ruber* (pink) and (d) *N. pachyderma*. Species occurrences (●) are overlaid on environmental suitability maps. Average test AUC scores (AUC) are measures of predictive performance and show the fit of MaxEnt models to test occurrence data not included in model calibration.

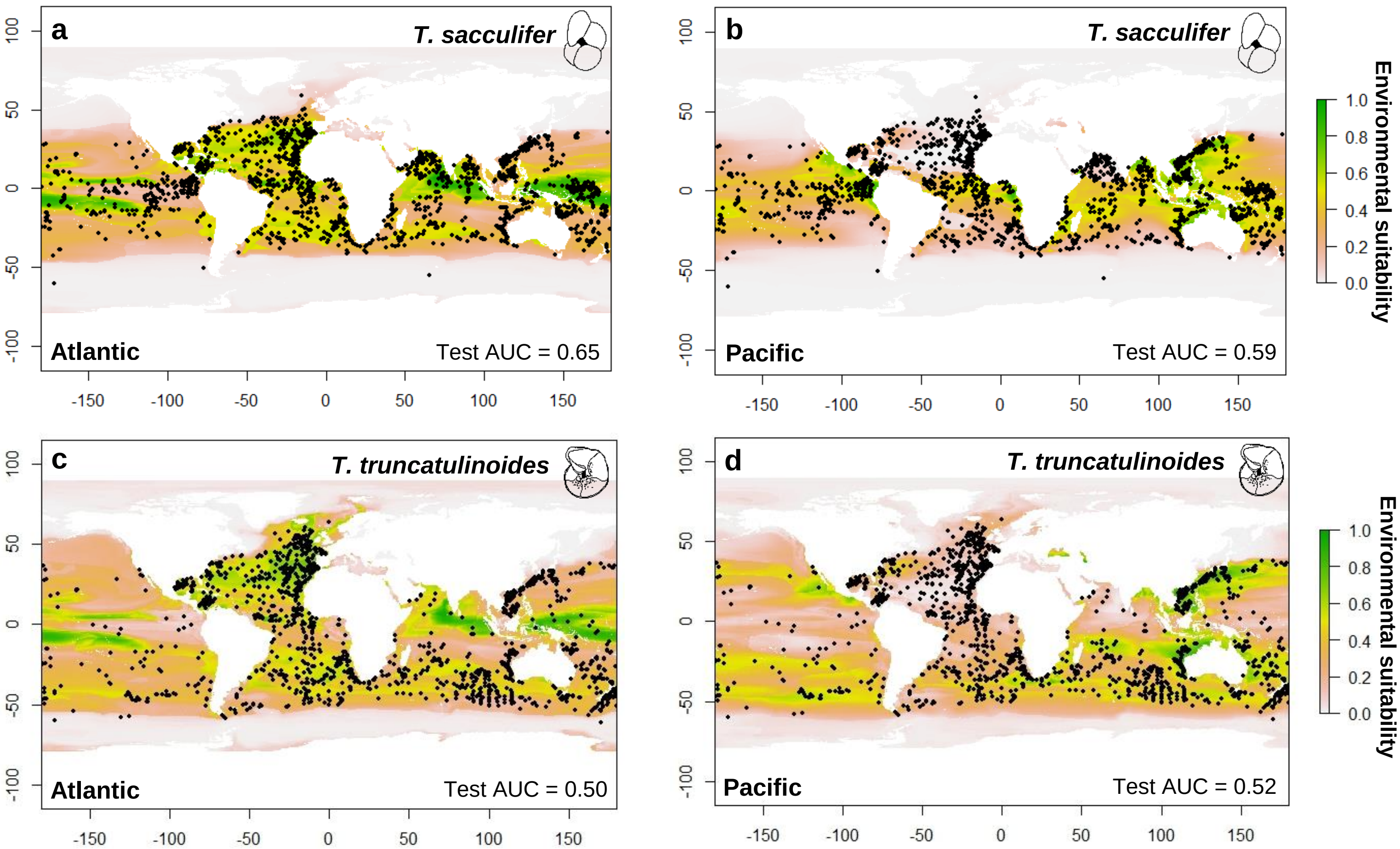

Figure S4a. MaxEnt ENMs of *T. sacculifer* and *T. truncatulinoides* calibrated in either the Atlantic (a, c) or Pacific (b, d) Oceans and projected to the modern global ocean. Models are calibrated with temperature of the coldest quarter. Species occurrences (●) are overlaid on environmental suitability maps. Average test AUC scores (AUC) are measures of predictive performance and show the fit of MaxEnt model projections to the remainder of global foraminifera occurrences not included in model calibration.

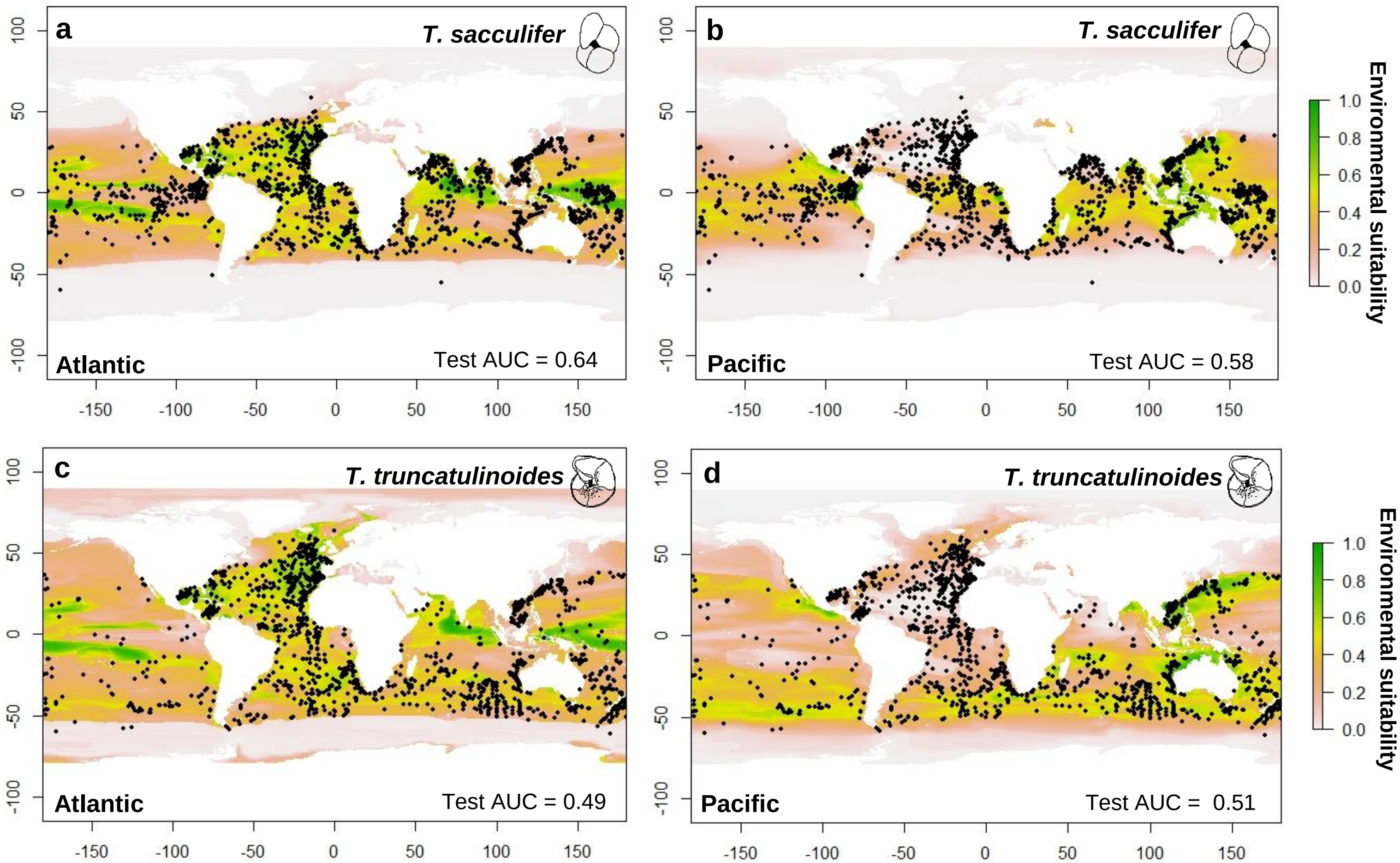

Figure S4b. MaxEnt ENMs of *T. sacculifer* and *T. truncatulinoides* calibrated in either the Atlantic (a, c) or Pacific (b, d) Oceans and projected to the modern global ocean. Models are calibrated with temperature of the warmest quarter. Species occurrences (●) are overlaid on environmental suitability maps. Average test AUC scores (AUC) are measures of predictive performance and show the fit of MaxEnt model projections to the remainder of global foraminifera occurrences not included in model calibration.

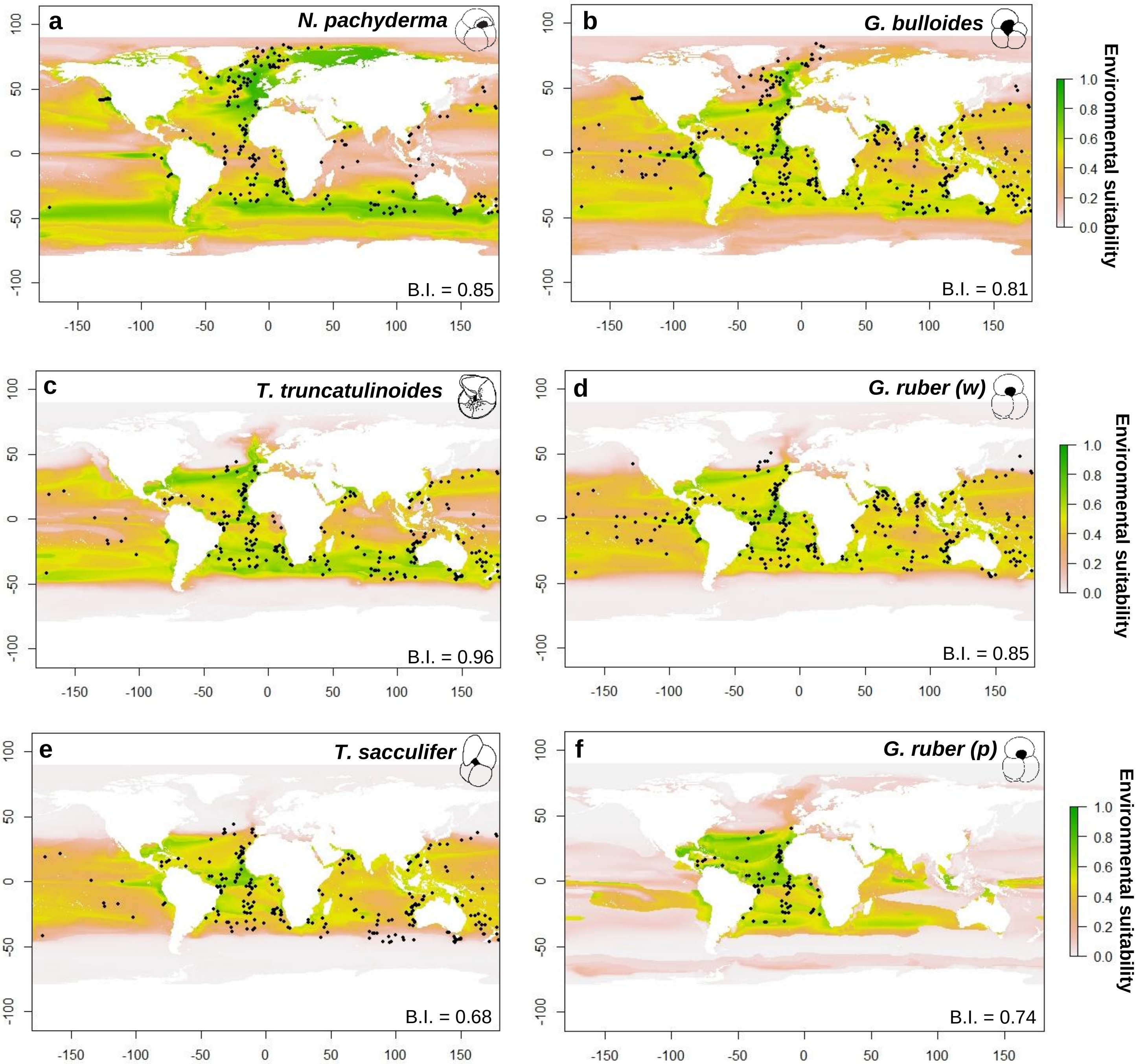

Figure S5a. MaxEnt global ENMs calibrated in the modern and projected to the LGM: (a) *Neogloboquadrina pachyderma*, (b) *Globigerina bulloides*, (c) *Truncororotalia truncatulinoides, (d) Globigerinoides ruber* (white), (e) *Trilobatus sacculifer*, and (f) *G. ruber* (pink). LGM species occurrences (●) are overlaid on the model projections of LGM environmental suitability. Models are calibrated with mean temperature of the coldest quarter. Dark green colour (and higher values) indicates high environmental suitability for species, light-green/yellow indicates intermediate suitability and pink/white (lower values) indicates poor suitability for species. Average Boyce indices (B.I.) are a measure of predictive performance and show the fit of MaxEnt model projections to LGM foraminifer species distributions.

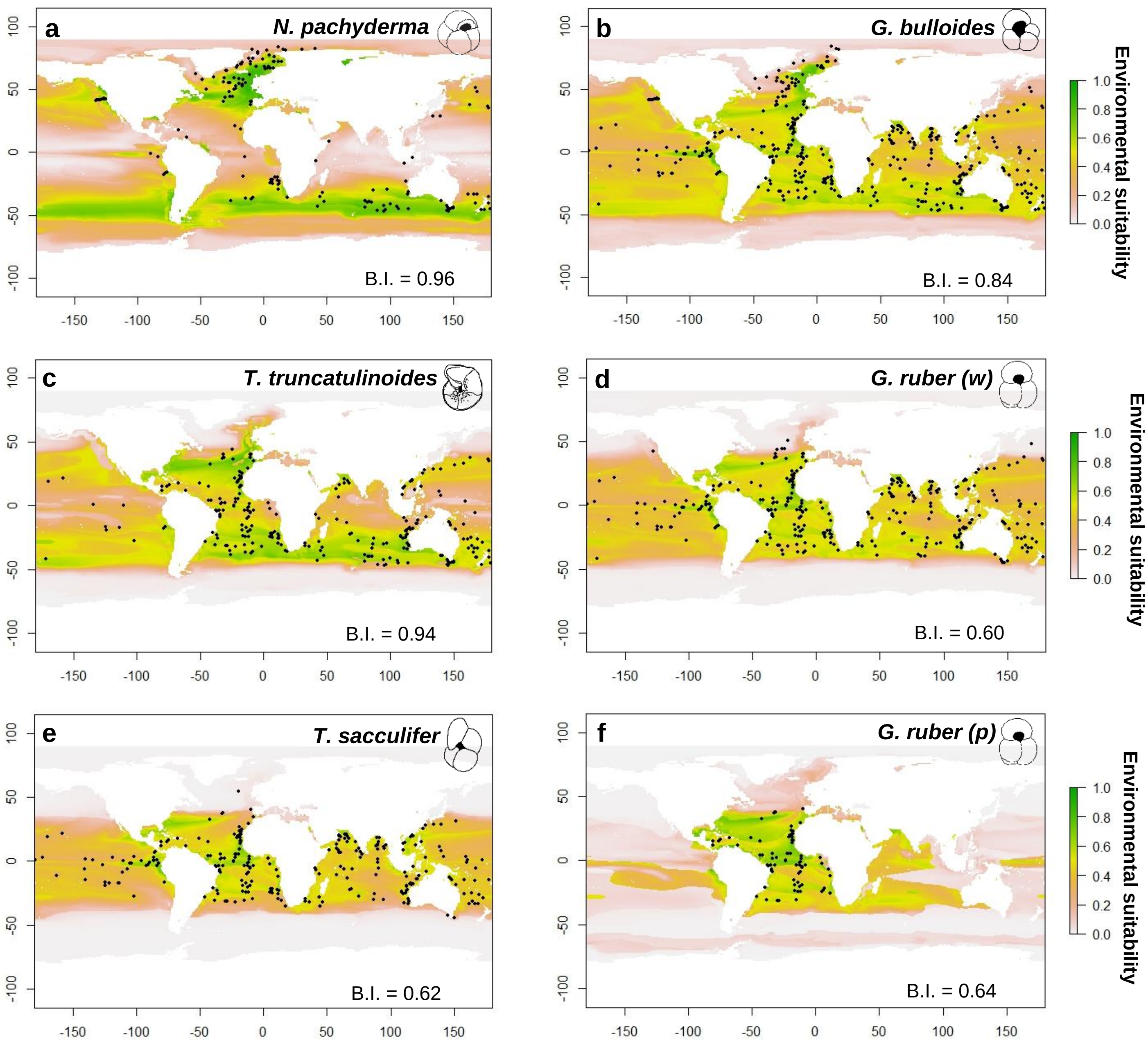

Figure S5b. MaxEnt global ENMs calibrated in the modern and projected to the LGM: (a) *Neogloboquadrina pachyderma*, (b) *Globigerina bulloides*, (c) *Truncororotalia truncatulinoides*, *(d) Globigerinoides ruber* (white), (e) *Trilobatus sacculifer*, and (f) *G. ruber* (pink). LGM species occurrences (●) are overlaid on the model projections of LGM environmental suitability. Models are calibrated with mean temperature of the warmest quarter. Dark green colour (and higher values) indicates high environmental suitability for species, light-green/yellow indicates intermediate suitability and pink/white (lower values) indicates poor suitability for species. Average Boyce indices (B.I.) are a measure of predictive performance and show the fit of MaxEnt model projections to LGM foraminifer species distributions.

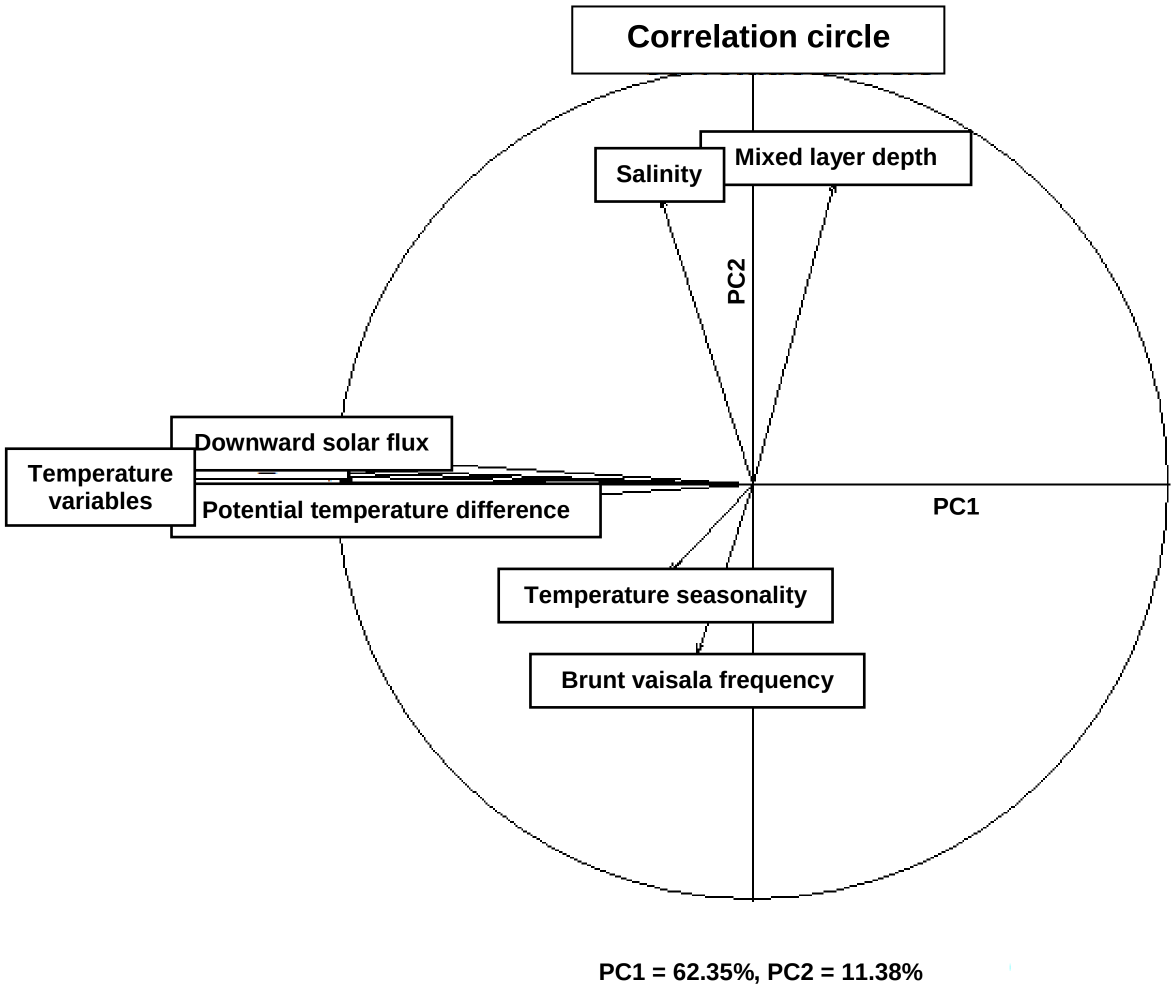

Figure S6. Correlation circle showing the contribution of individual environmental variables to the two principal component axes (PC1 = 62.35% and PC2 = 11.38%). PC1 is mainly represented by temperature and other variables highly correlated to this (downward solar flux and potential temperature differences). PC2 is mainly represented by salinity, mixed layer depth and the brunt vaisala frequency.

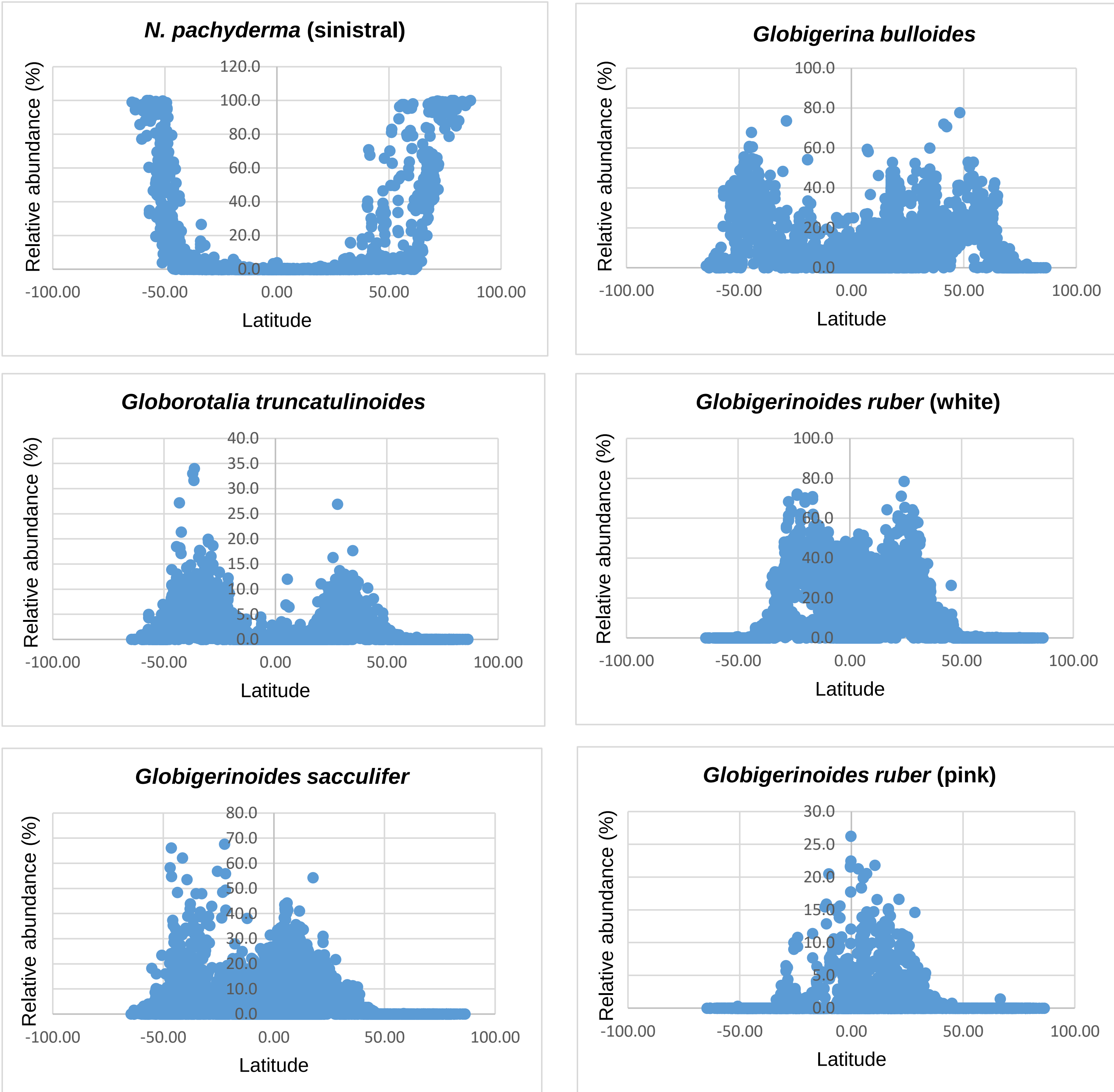

Figure S7. Planktic foraminifera relative abundance (%) vs latitude.

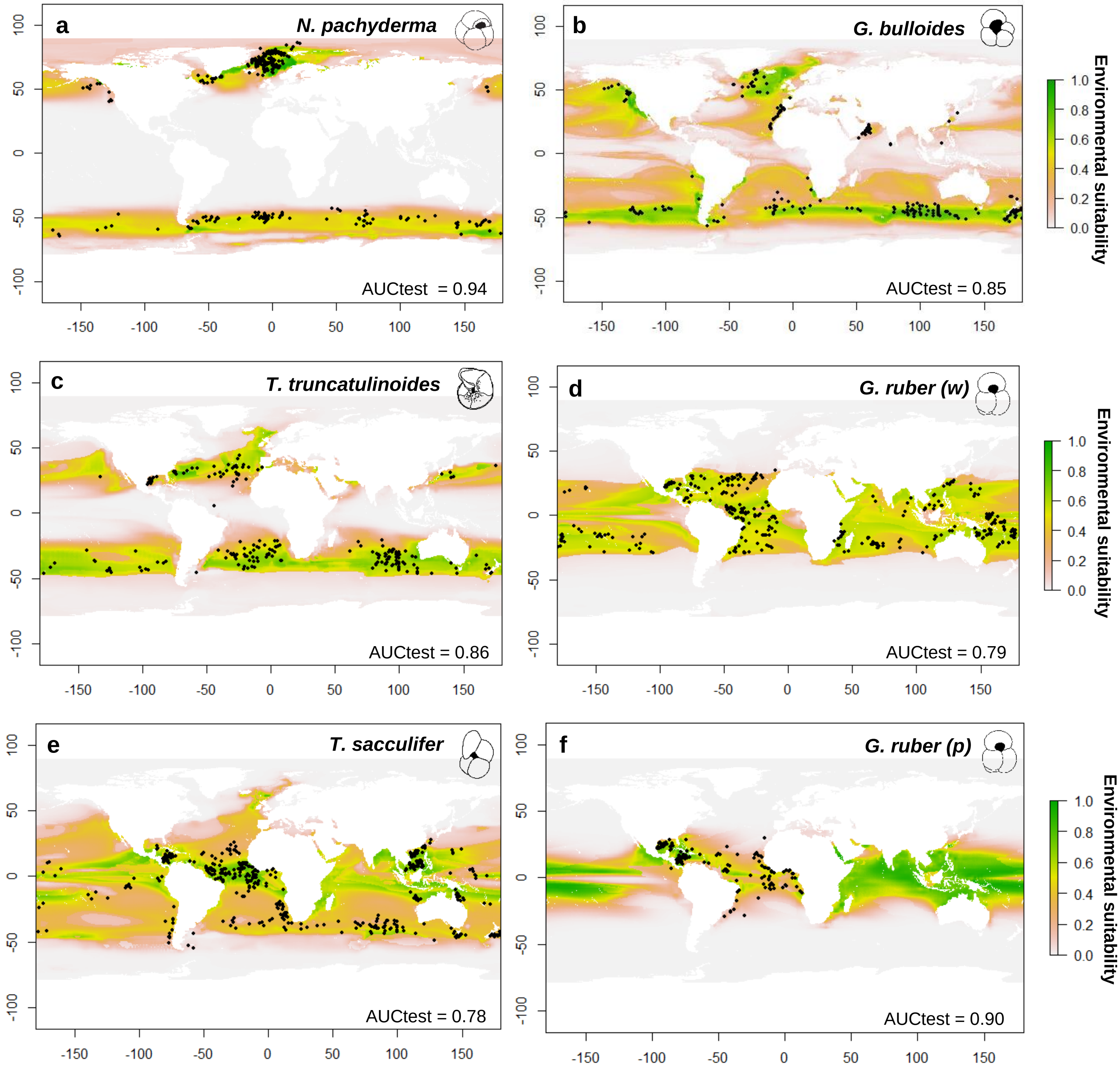

Figure S8a. MaxEnt optimum ENMs calibrated in the modern ocean projected globally: (a) *Neogloboquadrina pachyderma*, (b) *Globigerina bulloides*, (c) *Truncorotalia truncatulinoides, (d) Globigerinoides ruber* (white), (e) *Trilobatus sacculifer*, and (f) *G. ruber* (pink). Models calibrated with mean temperature of the coldest quarter. Modern species occurrences (●) are overlaid on the model projections of environmental suitability. Dark green colour (and higher values) indicates high environmental suitability for species, light-green/yellow indicates intermediate suitability and pink/white (lower values) indicates poor suitability for species. Average test AUC scores (AUC) are a measure of predictive performance and show the fit of MaxEnt models to test occurrence data not included in model calibration.

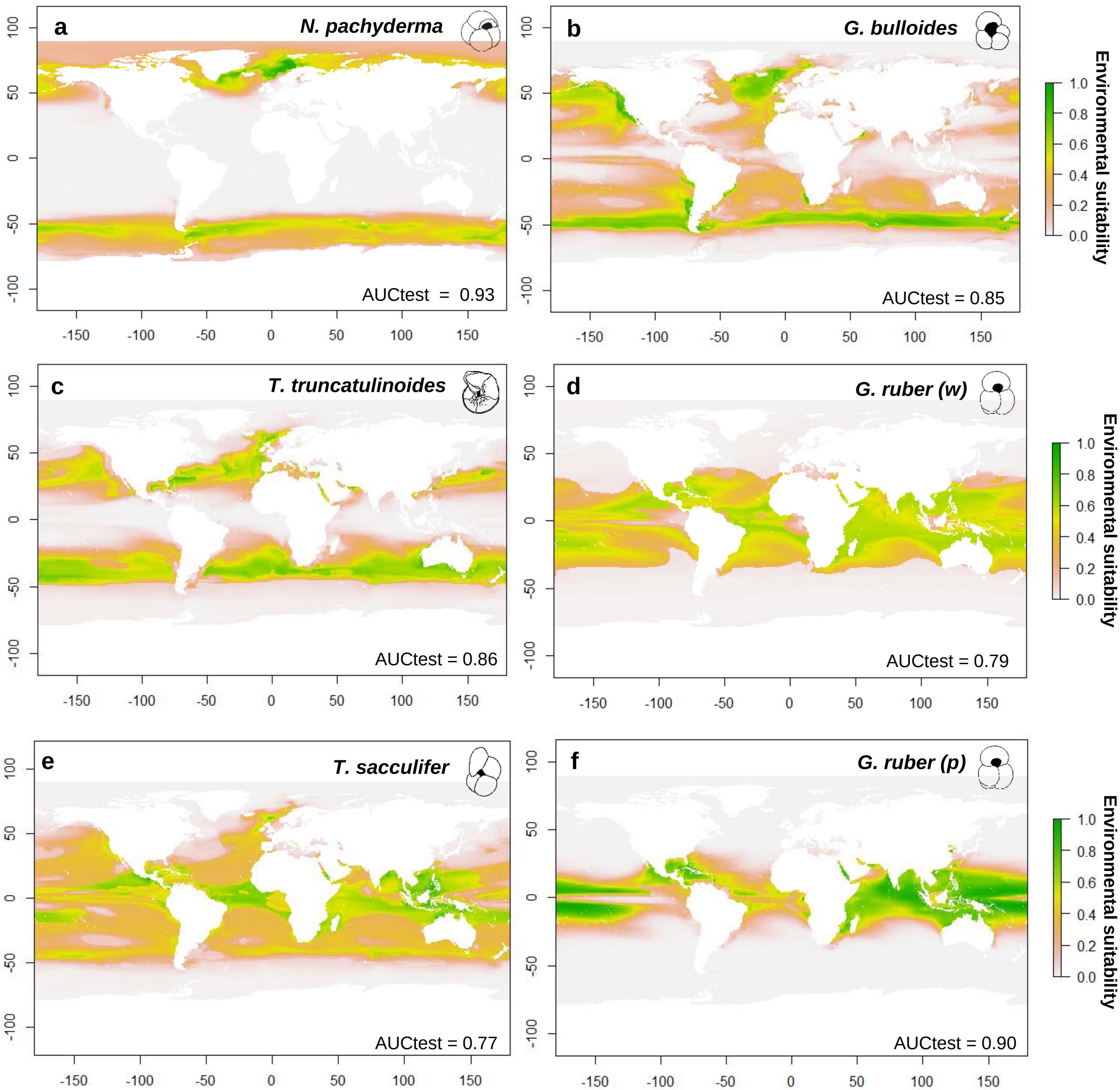

Figure S8b. MaxEnt optimum ENMs calibrated in the modern ocean and projected globally: (a) *Neogloboquadrina pachyderma*, (b) *Globigerina bulloides*, (c) *Truncorotalia truncatulinoides*, *(d) Globigerinoides ruber* (white), (e) *Trilobatus sacculifer*, and (f) *G. ruber* (pink). Models calibrated with mean temperature of the warmest quarter. Dark green colour (and higher values) indicates high environmental suitability for species, light-green/yellow indicates intermediate suitability and pink/white (lower values) indicates poor suitability for species. Average test AUC scores (AUC) are a measure of predictive performance and show the fit of MaxEnt models to test occurrence data not included in model calibration.

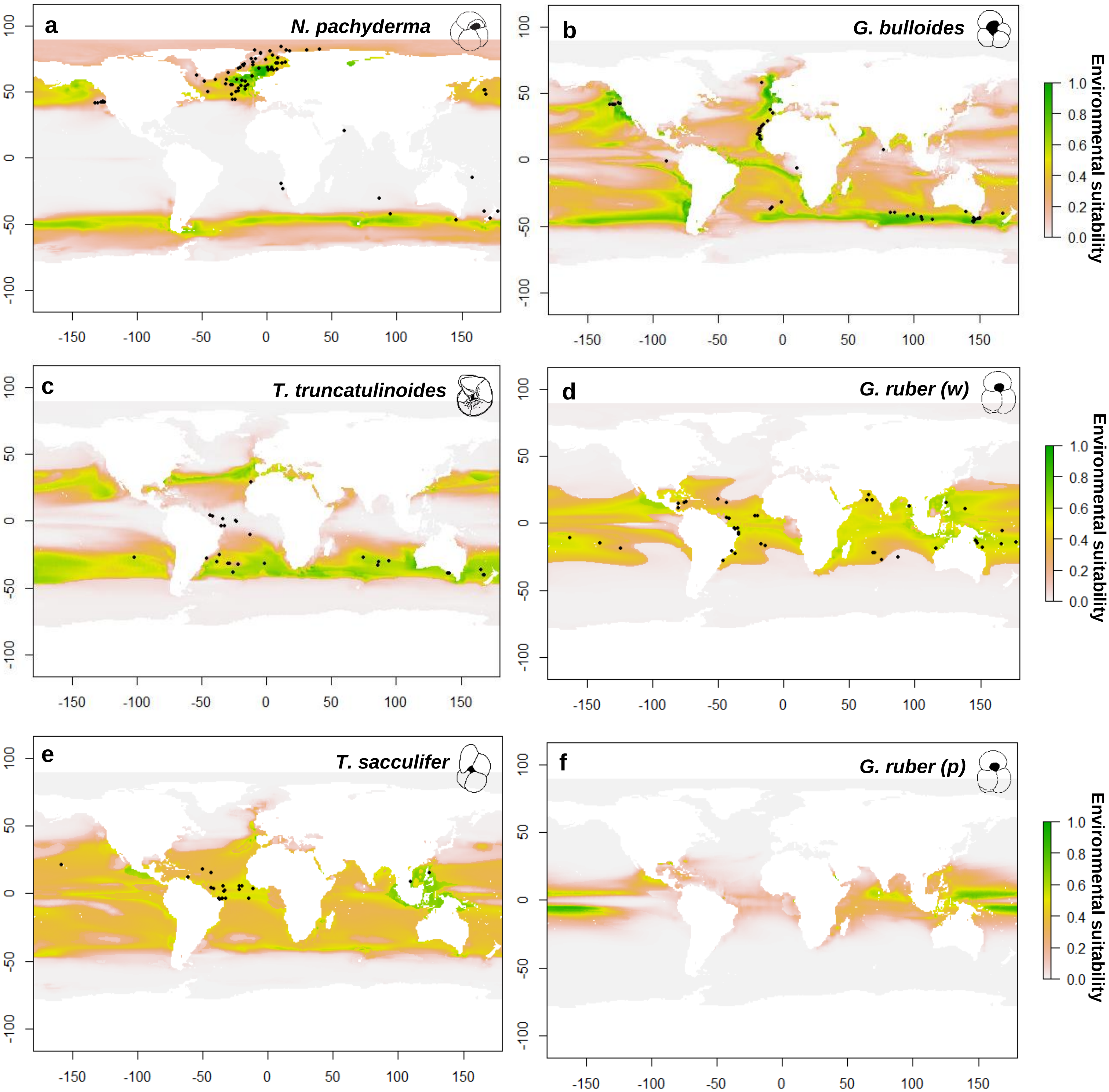
a
N. pachyderma
b
G. bulloides
c
T. truncatulinoides
d
G. ruber (w)
e
T. sacculifer
f
G. ruber (p)
Environmental suitability
1.0
0.8
0.6
0.4
0.2
0.0
100
50
0
-50
-100
-150
150

Figure S8c. MaxEnt optimum ENMs calibrated in the modern and projected to the LGM: (a) *Neogloboquadrina pachyderma*, (b) *Globigerina bulloides*, (c) *Truncororotalia truncatulinoides, (d) Globigerinoides ruber* (white), (e) *Trilobatus sacculifer*, and (f) *G. ruber* (pink). LGM species occurrences (●) are overlaid on the model projections of LGM environmental suitability. Models are calibrated with mean temperature of the warmest quarter. Dark green colour (and higher values) indicates high environmental suitability for species, light-green/yellow indicates intermediate suitability and pink/white (lower values) indicates poor suitability for species.

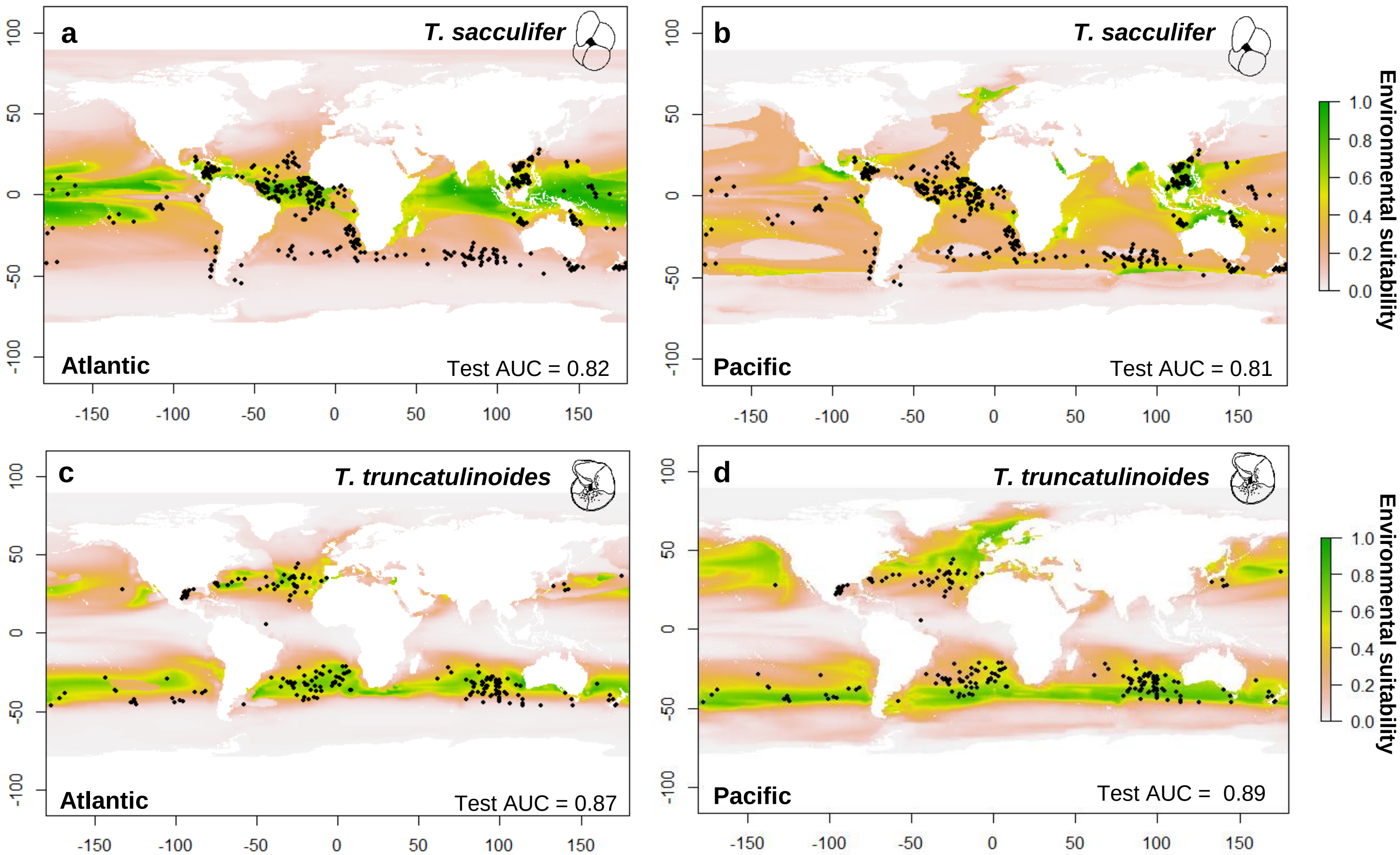

Figure S8d. MaxEnt optimum ENMs of *T. sacculifer* and *T. truncatulinoides* calibrated in either the Atlantic (a, c) or Pacific (b, d) Oceans and projected to the modern global ocean. Models are calibrated with temperature of the warmest quarter. Species occurrences (●) are overlaid on environmental suitability maps. Average test AUC scores (AUC) are measures of predictive performance and show the fit of MaxEnt model projections to the remainder of global foraminifera occurrences not included in model calibration.

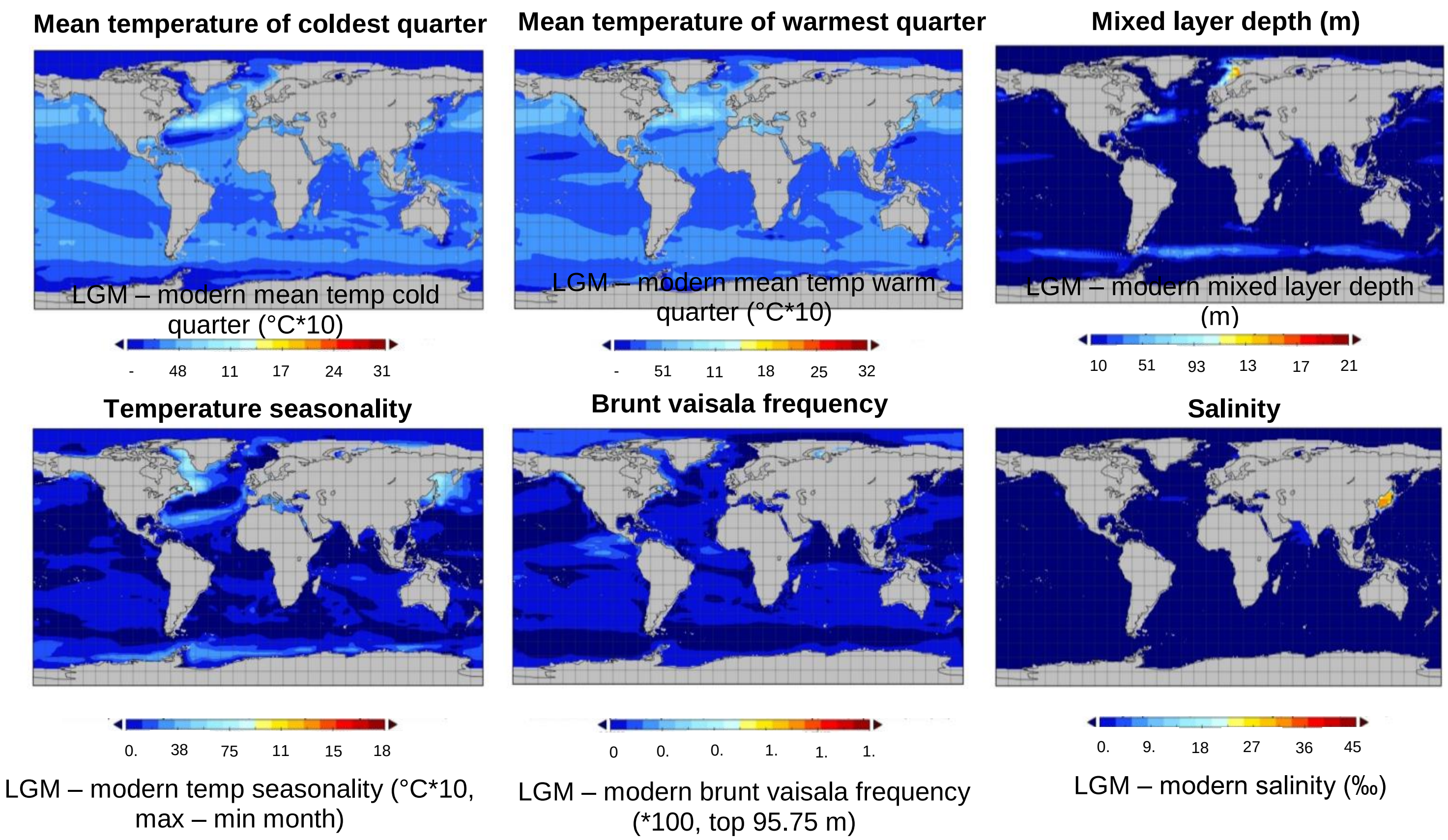

Figure S9. Difference between environmental variables included in ENM analyses, between the LGM and modern: (a) mean temperature of coldest quarter, (b) mean temperature of warmest quarter, (c) mixed layer depth, (d) temperature seasonality, (e) brunt vaisala frequency and, (f) salinity.

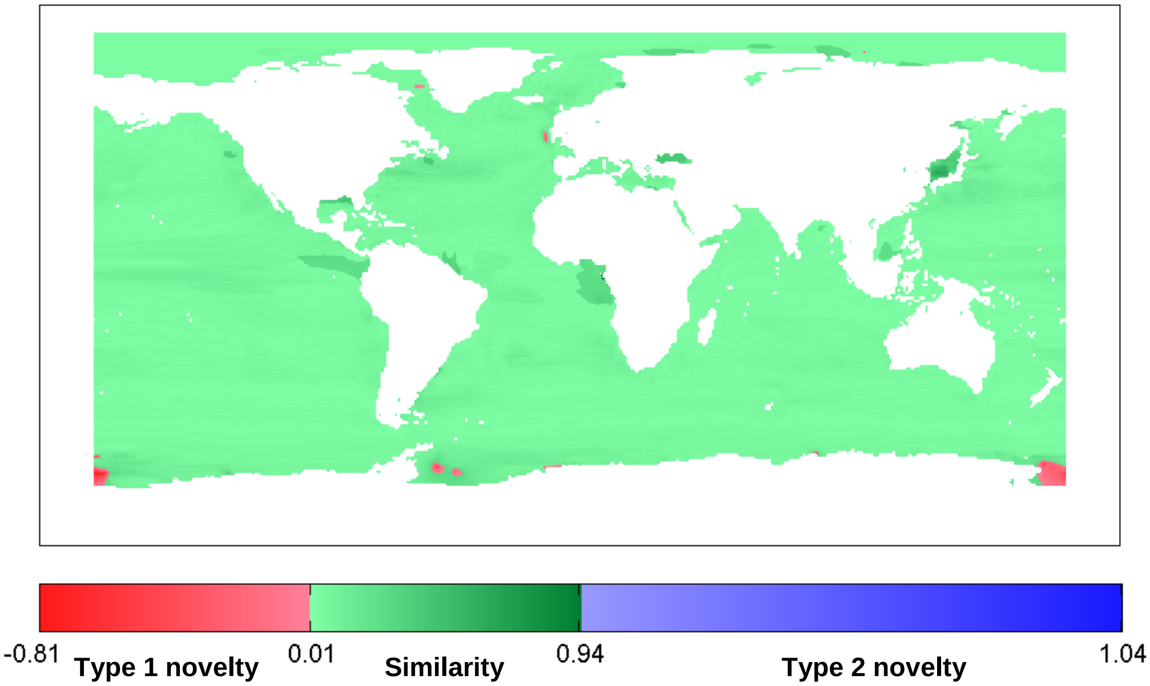

Figure S10. Map documenting non-analogue environmental space between the modern and LGM oceans. Green = regions of similar climate variables in both timeslices (0 indicates maximum similarity), red = regions with at least one variable outside of the modern univariate range (type 1 novelty). The more negative the value of the type 1 novelty, the less similar the climates are in these regions between the two timeslices. Blue = regions within the univariate range but with novel combinations between covariates (type 2 novelty).

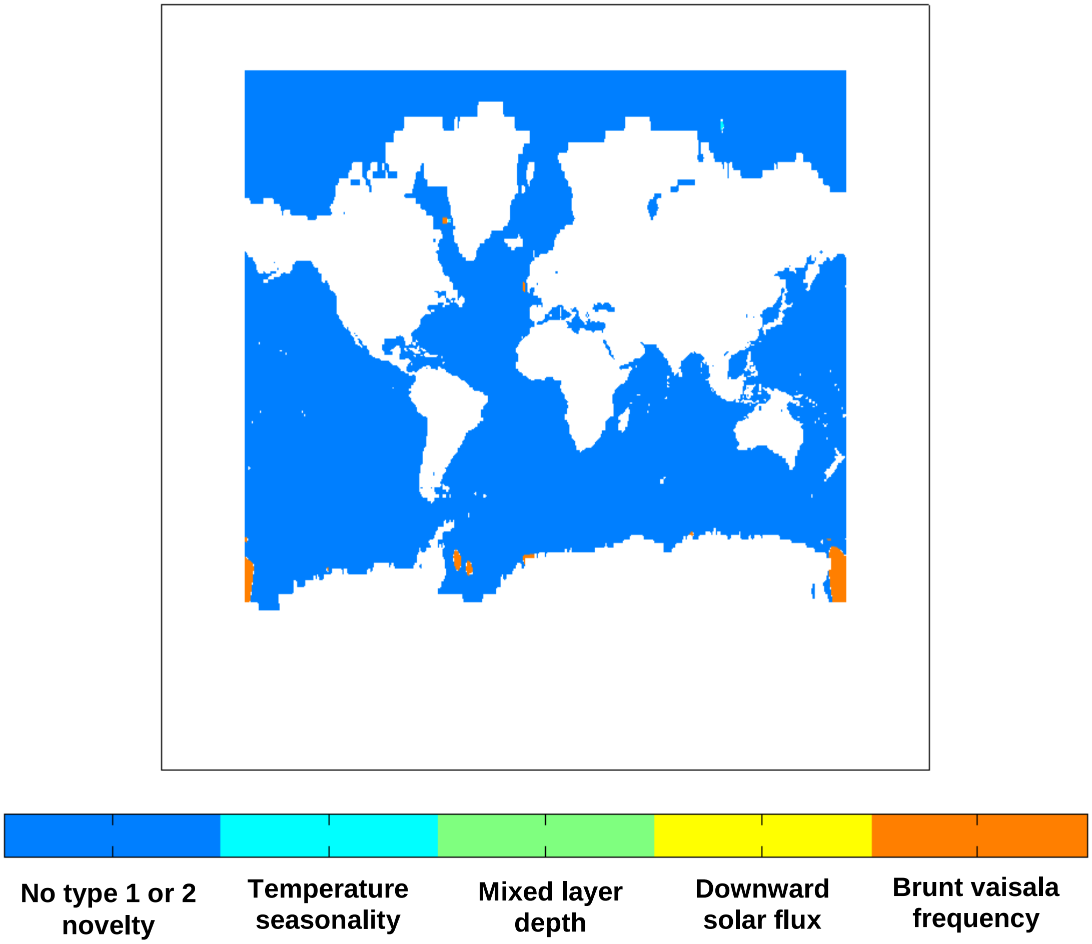

Figure S11. Environmental variables most influential on type 1 and 2 novelties (type 1 = regions with at least one variable outside the univariate range of climate space, type 2 = regions within the univariate range but with novel combinations between covariates) in non-analogue climate regions between the LGM with modern-day.

	bio1	bio4	bio8	bio9	bio10	bio11	ext1ann	ext2ann	ext3ann	ext4ann	ext5ann
bio1	1.00	0.14	0.99	0.99	0.99	1.00	0.79	-0.07	0.97	0.15	0.36
bio4	0.25	1.00	0.14	0.14	0.24	0.05	-0.01	0.04	0.17	-0.06	0.03
bio8	1.00	0.24	1.00	0.98	0.99	0.99	0.80	-0.10	0.97	0.15	0.36
bio9	1.00	0.25	0.99	1.00	0.99	0.99	0.77	-0.05	0.97	0.15	0.36
bio10	0.99	0.34	0.99	0.99	1.00	0.98	0.78	-0.07	0.97	0.14	0.36
bio11	1.00	0.16	0.99	0.99	0.98	1.00	0.80	-0.07	0.97	0.16	0.36
ext1ann	0.81	0.12	0.81	0.80	0.79	0.81	1.00	-0.26	0.76	0.15	0.19
ext2ann	-0.25	-0.09	-0.26	-0.24	-0.25	-0.25	-0.33	1.00	0.01	-0.17	0.05
ext3ann	0.97	0.31	0.96	0.96	0.97	0.95	0.75	-0.19	1.00	0.12	0.36
ext4ann	0.07	-0.04	0.07	0.07	0.07	0.08	0.07	-0.15	0.04	1.00	0.01
ext5ann	0.06	-0.14	0.05	0.06	0.04	0.07	-0.03	0.22	0.05	-0.04	1.00

Table S1. Pair-wise correlation heat map between environmental variables; the cells to the right of the centre diagonal show the correlation between modern covariates and the cells to the left of the centre diagonal are the correlation coefficients for the Last Glacial Maximum covariates. Environmental labels are bio1 = annual mean temperature, bio4 = temperature seasonality (max – min month), bio8 = mean temperature of wettest quarter, bio9 = mean temperature of driest quarter, bio10 = mean temperature of warmest quarter, bio11 = mean temperature of coldest quarter, ext1ann = downward solar flux (Wm^{-2}), ext2ann = mixed layer depth (between 0-300 m), ext3ann = potential temperature difference (between 0-200 m water depth), ext4ann = brunt vaisala frequency, and ext5ann = salinity.

	Variable importance (cold)									
	Mean temperature of coldest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
N. pachyderma	77.5	75.6	5.7	5.4	9.6	8.1	0.4	1.3	6.8	9.7
G. bulloides	54.3	37.2	12.3	26.5	17.3	16.5	0.2	1.5	15.9	18.3
T. truncatulinoides	46.3	35.9	25.8	37.5	4.6	6.6	1.0	1.2	22.4	18.9
G. ruber (w)	79.1	56.4	5.7	19.8	5.0	8.2	0.2	1.8	10.0	13.7
T. sacculifer	85.5	66.3	4.0	15.8	4.2	8.0	0.2	1.6	6.2	8.4
G. ruber (p)	8.9	13.6	1.4	3.0	3.3	8.7	0.2	1.1	86.3	73.6
	Variable importance (warm)									
	Mean temperature of warmest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
N. pachyderma	72.0	72.9	9.9	8.3	11.1	7.8	0.5	1.3	6.5	9.6
G. bulloides	56.9	37.7	10.7	18.4	12.3	16.1	0.3	1.8	19.7	26.0
T. truncatulinoides	44.9	36.7	21.0	26.6	5.5	7.7	0.3	1.6	28.3	27.4
G. ruber (w)	79.5	57.5	4.2	11.6	3.0	8.2	0.1	1.3	13.1	21.4
T. sacculifer	87.2	71.5	2.3	7.5	2.8	6.8	0.1	0.9	7.6	13.3
G. ruber (p)	8.0	10.3	1.7	4.9	2.5	6.0	0.3	0.7	87.5	78.2

Table S2. The contribution (%) and permutation importance (PI) of selected environmental variables to planktic foraminiferal global modern ENMs derived from MaxEnt. Percentage contribution is calculated based on how much the variable contributed to the model depending on the path selected for a particular run – as the model is trained it tracks which environmental variables contribute to fitting the model. These values are heuristically defined and depend on the particular path MaxEnt used to obtain the optimal solution. Permutation importance is determined by varying the predictor values between presence and background points, and examining the change in AUC (a threshold independent measure of ENM predictive performance). A large decrease in AUC values indicates that the model fit is heavily dependent on that variable. This measure is dependent only on the final model and not the path used to obtain it for a particular run (Phillips et al. 2006; Peterson et al. 2011).

	Variable importance (cold, Atlantic)									
	Mean temperature of coldest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
T. truncatulinoides	39.5	36.8	8.5	13.8	5.5	4.8	5.2	5.6	41.2	39.0
T. sacculifer	63.1	54.0	4.8	9.4	1.4	1.2	1.0	5.5	29.7	29.9
	Variable importance (warm, Atlantic)									
	Mean temperature of warmest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
T. truncatulinoides	39.8	34.4	9.3	14.1	5.4	6.4	6.3	5.7	39.1	39.3
T. sacculifer	65.3	48.3	4.2	10.8	0.9	2.6	0.7	3.4	29.0	34.9
	Variable importance (cold, Pacific)									
	Mean temperature of coldest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
T. truncatulinoides	39.3	38.6	32.1	38.3	11.0	12.4	0.0	0.2	17.6	10.5
T. sacculifer	75.2	69.1	7.1	15.6	11.6	11.4	1.9	0.6	4.2	3.4
	Variable importance (warm, Pacific)									
	Mean temperature of warmest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
T. truncatulinoides	42.6	43.7	30.5	34.9	10.4	12.8	0.2	0.1	16.4	8.5
T. sacculifer	83.9	78.9	3.1	5.5	8.3	11.6	1.3	0.6	3.4	3.4

Table S3. The contribution (%) and permutation importance (PI) of selected environmental variables to planktic foraminiferal regional ENMs (calibrated in either the modern Atlantic or Pacific Ocean) derived from MaxEnt.

	Variable importance (cold, North Atlantic)									
	Mean temperature of coldest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
N. pachyderma	80.0	77.9	14.7	18.5	1.9	1.5	0.0	0.0	3.4	2.1
G. ruber (p)	48.1	60.8	15.2	21.8	4.6	6.2	4.2	7.0	28.0	4.2
	Variable importance (cold, North Atlantic - depth subset)									
	Mean temperature of coldest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
N. pachyderma	73.1	78.3	19.6	19.7	5.0	1.7	0.0	0.0	2.3	0.4
G. ruber (p)	52.1	43.7	32.5	38.4	6.7	6.1	8.5	11.1	0.2	0.7
	Variable importance (warm, North Atlantic)									
	Mean temperature of warmest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
N. pachyderma	78.4	79.7	6.8	12.3	5.9	3.6	0.0	0.0	8.9	4.4
G. ruber (p)	47.4	59.1	18.7	22.8	3.6	6.5	6.4	5.8	23.9	5.9
	Variable importance (warm, North Atlantic - depth subset)									
	Mean temperature of warmest Q		Temperature seasonality		Mixed layer depth		Brunt vaisala frequency		Salinity	
Species	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI	% contribution	PI
N. pachyderma	76.8	79.7	7.9	16.9	6.8	2.2	0.1	0.0	8.4	1.3
G. ruber (p)	39.7	48.7	40.6	36.3	10.9	6.3	8.6	8.7	0.2	0.0

Table S4. The contribution (%) and permutation importance (PI) of selected environmental variables to planktic foraminiferal ENMs calibrated in the modern Atlantic Ocean with differing preservation states as determined by MaxEnt.

Species	Niche overlap (D)	Niche equivalency significance (p value)	Niche similarity significance (p value)	Expansion (%)	Stability (%)	Unfilling (%)
N. pachyderma	0.64	0.18	0.01	0.0017	0.9983	0.0000
G. bulloides	0.64	0.18	0.01	0.0000	1.0000	0.0013
T. truncatulinoides	0.87	0.18	0.01	0.0020	0.9980	0.0000
G. ruber (w)	0.75	0.18	0.01	0.0004	0.9996	0.0000
T. sacculifer	0.72	0.18	0.01	0.0015	0.9985	0.0000
G. ruber (p)	0.69	0.18	0.01	0.0086	0.9914	0.0000

Table S5. Ordination analyses of planktic foraminifera environmental niche margin change between the LGM and modern. Values of niche overlap (Schoener's D), expansion (%), stability (%) and unfilling (%) are shown along with significance values for niche equivalency and similarity tests.

	Variable importance (cold)							
Species	**Mean temp of coldest Q**		**Temperature seasonality**		**Mixed layer depth**		**Brunt vaisala frequency**	
	% contribution	**PI**	**% contribution**	**PI**	**% contribution**	**PI**	**% contribution**	**PI**
N. pachyderma	85.3	83.8	6.6	8.9	8	7	0	0.3
G. bulloides	77.2	67.2	14	21.3	8.7	11.3	0	0.2
G. truncatulinoides	64.7	62.8	24.7	21.4	10.6	15.7	0	0
G. ruber (white)	92.2	77.9	0.7	6.6	5.5	13.9	1.7	1.7
T. sacculifer	67.7	62.6	17.9	19	13.9	16.8	0.5	1.5
G. ruber (pink)	89.3	82	4.5	11.3	4.2	4.4	2	2.3
	Variable importance (warm)							
Species	**Mean temp of coldest Q**		**Temperature seasonality**		**Mixed layer depth**		**Brunt vaisala frequency**	
	% contribution	**PI**	**% contribution**	**PI**	**% contribution**	**PI**	**% contribution**	**PI**
N. pachyderma	88.2	85.2	3.5	8	8.2	6.6	0.1	0.1
G. bulloides	71.8	59.3	17.1	28	11	12.6	0	0.1
T. truncatulinoides	35.8	46.6	44.5	34.8	19.6	18.6	0	0
G. ruber (white)	90	78	4.4	10.6	3.3	9.8	2.3	1.6
T. sacculifer	69.9	63.4	21.5	24.6	7.6	10.3	1	1.7
G. ruber (pink)	91.5	87.1	2.2	5.3	5	5.7	1.4	1.9

Table S6. The contribution (%) and permutation importance (PI) of selected environmental variables to planktic foraminiferal global modern optimal ENMs derived from MaxEnt.

	Variable importance (cold Atlantic)							
Species	**Mean temp of coldest Q**		**Temperature seasonality**		**Mixed layer depth**		**Brunt vaisala frequency**	
	% contribution	**PI**	**% contribution**	**PI**	**% contribution**	**PI**	**% contribution**	**PI**
T. sacculifer	74.5	64.2	11.5	16.7	9.6	15.3	4.4	3.8
T. truncatulinoides	69.1	64.6	27.1	23.4	3.8	11.5	0	0.4
	Variable importance (warm Atlantic)							
Species	**Mean temp of coldest Q**		**Temperature seasonality**		**Mixed layer depth**		**Brunt vaisala frequency**	
	% contribution	**PI**	**% contribution**	**PI**	**% contribution**	**PI**	**% contribution**	**PI**
T. sacculifer	62.1	60.2	21.7	24.2	12.4	10.2	3.7	5.4
T. truncatulinoides	45.3	55.9	43.8	32.1	10.9	11.8	0	0.1
	Variable importance (cold Pacific)							
Species	**Mean temp of coldest Q**		**Temperature seasonality**		**Mixed layer depth**		**Brunt vaisala frequency**	
	% contribution	**PI**	**% contribution**	**PI**	**% contribution**	**PI**	**% contribution**	**PI**
T. sacculifer	63.8	67.1	29.3	28.5	6.7	4.2	0.2	0.2
T. truncatulinoides	86	84.1	10.9	12.1	3	3.2	0.1	0.6
	Variable importance (warm Pacific)							
Species	**Mean temp of coldest Q**		**Temperature seasonality**		**Mixed layer depth**		**Brunt vaisala frequency**	
	% contribution	**PI**	**% contribution**	**PI**	**% contribution**	**PI**	**% contribution**	**PI**
T. sacculifer	77.5	80.5	19.5	15.7	2.6	3.7	0.4	0.1
T. truncatulinoides	50.5	47.3	36.3	39.2	13.1	13.5	0	0

Table S7. The contribution (%) and permutation importance (PI) of selected environmental variables to planktic foraminiferal regional optimal ENMs (calibrated in either the modern Atlantic or Pacific Ocean) derived from MaxEnt.

Global (cold)			
Species	**AUCtest**	**AUCtrain**	**AUCdiff**
N. pachyderma	0.9401	0.946	0.0059
G. bulloides	0.8475	0.8648	0.0173
G. truncatulinoides	0.8563	0.8625	0.0062
G. ruber (white)	0.7931	0.8071	0.014
T. sacculifer	0.7762	0.7908	0.0146
G. ruber (pink)	0.8963	0.9039	0.0076
Global (warm)			
Species	**AUCtest**	**AUCtrain**	**AUCdiff**
N. pachyderma	0.929	0.9341	0.0051
G. bulloides	0.8497	0.8632	0.0135
G. truncatulinoides	0.8653	0.8765	0.0112
G. ruber (white)	0.7728	0.7915	0.0187
T. sacculifer	0.7734	0.7855	0.0121
G. ruber (pink)	0.8952	0.9011	0.0059

Table S8. Average AUCtest, AUCtrain and AUCdiff (AUCtrain – AUCtest) values for globally calibrated planktic foraminiferal modern MaxEnt ENMs.

Pacific (warm)			
Species	**AUCtest**	**AUCtrain**	**AUCdiff**
T. truncatulinoides	0.8778	0.8932	0.0154
T. sacculifer	0.8089	0.8331	0.0242
Pacific (cold)			
Species	**AUCtest**	**AUCtrain**	**AUCdiff**
T. truncatulinoides	0.8925	0.9047	0.0122
T. sacculifer	0.8124	0.8472	0.0348
Atlantic (warm)			
Species	**AUCtest**	**AUCtrain**	**AUCdiff**
T. truncatulinoides	0.8653	0.8782	0.0129
T. sacculifer	0.8179	0.8318	0.0139
Atlantic (cold)			
Species	**AUCtest**	**AUCtrain**	**AUCdiff**
T. truncatulinoides	0.8645	0.8755	0.011
T. sacculifer	0.8234	0.8388	0.0154

Table S9. Average AUCtest, AUCtrain and AUCdiff (AUCtrain – AUCtest) values for regionally calibrated planktic foraminiferal modern MaxEnt ENMs.

Species	Niche overlap (D)	Niche similarity significance (p value)	Expansion (%)	Stability (%)	Unfilling (%)
N. pachyderma	0.45	0.01	0	~99	10
G. bulloides	0.74	0.01	~4	~95	1
T. truncatulinoides	0.19	0.19	19	~81	~2
G. ruber (white)	0.54	0.54	~9	~91	0
T. sacculifer	0.03	0.03	~58	~42	0
G. ruber (pink)	0.34	0.01	~18	~74	0

Table S10. Ordination analyses of planktic foraminifera environmental optimum niche margin change between the LGM and modern. Values of niche overlap (Schoener's D), expansion (%), stability (%) and unfilling (%) are shown along with significance values for niche similarity tests.

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